Transportation Engineering 12 (2023) 100167

Contents lists available at ScienceDirect

Transportation Engineering

journal homepage: www.sciencedirect.com/journal/transportation-engineering

A flexible approach to select road traffic counting locations: System design and application of a fuzzy Delphi analytic hierarchy process

Gregorio Gecchele [a], Riccardo Ceccato [b,*], Riccardo Rossi [b], Massimiliano Gastaldi [b,c]

[a] Atraki s.r.l., Sant'Ambrogio di Valpolicella, 37015 Italy
[b] Department of Civil, Architectural and Environmental Engineering, University of Padova, Via Marzolo, 9, 35131 Padova, Italy
[c] Department of General Psychology, University of Padova, Via Venezia, 8, 35131 Padova, Italy

ARTICLE INFO

Keywords:
Multi-criteria decision-making
Road traffic monitoring
Sensor location problem

ABSTRACT

Although the diffusion of Information and Communication Technologies provided transportation analysists with new data sources (such as Floating Car and mobile devices), the use of permanent sensors installed on roads is still of paramount importance for traffic analysis. Continuous count stations are one of the main components of a road traffic monitoring program, which could fulfil several aims: (1) planning of a transportation system, (2) traffic management and operations, (3) improvement of road safety, (4) special monitoring for planned/emergency events, and (5) estimation of environmental impacts. In this research activity a Fuzzy Delphi Analytic Hierarchy Process (FDAHP) was applied to select the best locations for a fixed number of permanent count stations, as the basis of a traffic monitoring program that can reach the previously described targets. A real case study was developed in the Città Metropolitana di Venezia (Italy), where budget limitations imposed the need for a scientific and sound framework to decide where new sensors should be installed. Specific objectives and criteria were defined, as well as proper indicators to quantify them using available data. Their relative importance was evaluated by a panel of experts belonging to several agencies, therefore with different perspectives. The information obtained was analysed following the FDAHP approach to produce a ranking of the potential locations. The proposed holistic approach can be considered as a reference framework for a system to support local authorities in creating a traffic monitoring system and can be easily applied to other study areas.

1. Introduction

Traffic monitoring is one of the essential activities to design and maintain an efficient, safe, and sustainable transportation system. In particular, data collected through a road Traffic Monitoring System (TMS) support many functions and decision processes at different levels [1]. This information can be used to manage short- and long-term plans, such as the design of infrastructure, the identification and scheduling of maintenance activities, the development of control strategies for road junctions, or the implementation of traffic regulations and restrictions. In addition, other sectors/activities that could benefit from a TMS are finance (e.g., to estimate revenues), legislation (e.g., to assess the enforcement of specific policies), safety (e.g., to predict and detect vehicle accidents), environmental analysis (e.g., to forecast vehicle emissions), and travellers (e.g., to get information about traffic). In recent years, the sources of information on traffic characteristics and performance have increased significantly due to the diffusion of Information and communication technologies [2]. Recent sources include Floating Car Data [3], mobile phone call data [4], social networking data [5] and images from unmanned aerial vehicles [6]. In many cases, such data are provided by the private sector and sold to public agencies. Nevertheless, transportation agencies often use information from permanent (or continuous) traffic monitoring sensors, that they purchase, install, and maintain [7]. Despite the relevance of a TMS, public agencies have to face with budget constraints, imposing limitations on the number of sensors to install. Therefore, the location of these instruments is of paramount importance for an optimal allocation of public resources. However, data collected can serve multiple, and potentially conflicting objectives. For this reason, multiple-criteria decision-making techniques can be useful in addressing the complexity of the problem [8], providing a support system for local agencies that need to design a proper TMS.

* Corresponding author.
E-mail addresses: gregorio.gecchele@atraki.it (G. Gecchele), riccardo.ceccato@dicea.unipd.it (R. Ceccato), riccardo.rossi@unipd.it (R. Rossi), massimiliano.gastaldi@unipd.it (M. Gastaldi).

https://doi.org/10.1016/j.treng.2023.100167
Received 20 September 2022; Received in revised form 9 January 2023; Accepted 27 February 2023
Available online 1 March 2023

The research presented in this paper is focused on the selection of the best locations for a fixed number of permanent road count sensors of a TMS. Specifically, the study aims to provide decision makers with a transparent and flexible framework to select sensor sites considering and depending on multiple objectives for which collected data can be used. The implemented approach is based on the Fuzzy Delphi Analytic Hierarchy Process and was applied to the case study of the Città Metropolitana di Venezia (Italy), where a panel of experts belonging to different agencies was involved.

The contents of the paper are organized as follows. In the next section, a literature review of the main topics of the work is reported, that are the problem of the location of traffic count sensors, the Analytic Hierarchy Process and the Fuzzy Delphi method. In the third section, the adopted methodology is described in detail, including a summary of the developed framework and the general steps of the Analytic Hierarchy Process and the Fuzzy Delphi approach. The fourth section is focused on the practical application of the proposed procedure, with a description of the study area, a presentation of results and their discussion. After that, final remarks and future research steps are reported in the last section.

2. Literature review

2.1. Location of traffic count sensors

Defining the optimal location of traffic sensors is not a recent research field [9]. Many previous authors developed several techniques to solve this problem [2]. Most of them are based on optimization methods [10–13], while other approaches have been proposed, such as graphical [14] and random processes [15]. However, most of previous works considered only one or few objectives that a TMS can satisfy, and, therefore, that can be included in the presented methodologies. The main one is the estimation of Origin/Destination (O/D) matrices, which are the essential input for traffic simulations [16–20]. Other objectives include direct estimation of traffic flows on network links [21,22] and travel time [23]. For this reason, to the best of authors' knowledge, the developed research is one of the first attempts to consider multiple objectives of a TMS in a procedure to select the location of traffic sensors.

2.2. Analytic hierarchy process

Multi-criteria decision making techniques have been largely adopted in many research fields, including transportation [24]. These procedures allow to address multiple and often conflicting criteria in the decision process, providing systematic and transparent approaches ensuring rational and efficient solutions [25,26]. One of the most diffused multi-criteria decision making techniques is the Analytic Hierarchy Process (AHP), developed by Saaty in the 1970s [27]. The AHP is a structured quantitative method that allows the decision maker (DM) to identify optimal alternatives by ranking them consistent with their estimated weights [28]. The technique is based on a framework in which the alternatives and criteria to evaluate them are organized in a hierarchical manner [25]. The performance of criteria and alternatives is quantified through a series of pairwise comparisons in which the DM has to judge the relative importance (weights) of these elements [24].

The method has several advantages. First, the hierarchical structure provided to DMs allows to better understand the link between prioritization of alternatives, multiple criteria to evaluate them and the final aim of the procedure, thus increasing the confidence of the DM [25]. Second, the adoption of paired comparisons helps to reduce the complexity of the decisions [26,29] and improves the accuracy of judgements (compared to a simultaneous evaluation of all the alternatives) [28]. Judgements are based on a verbal ratio scale, thus without units in the comparisons; moreover, it allows to consider both qualitative and quantitative criteria and alternatives [28]. In addition, the AHP embeds a robust procedure to verify the consistency of DM's evaluations [26]. However, a high number of pairwise comparisons could increase the likelihood of having inconsistent judgements and the effort to perform them [28].

One of the major limitations of the AHP is the assumption of independence among the considered criteria. Specifically the method can be adopted to calculate weights of criteria when they are independent and outer-dependent by the upper-level items [30]. The approach does not allow the items of the hierarchical levels to have dependence and feedback with each involved element, thus neglecting inner effects [31]. However, in many real applications, selecting enough independent criteria is difficult [32]; in addition, several problems cannot be structured in a hierarchical framework since they involve the interaction and dependence of elements [33]. Moreover, rank reversal occurs in AHP, i.e. the addition or removal of an alternative leads to change in weights of other items, thus altering the final ranking [32,34,35]. Furthermore, the method assigns equal importance to each provided priority, neglecting the potential disparities in respondents' profiles; therefore, a specific sensitivity analysis is needed to identify the individuals who most severely affect the final results [36]. Lastly, AHP is limited to static decisions [37].

Despite these shortcomings, the AHP has been extensively adopted in transportation, particularly for project appraisals [8,25,29,38]. Previous works implemented the method to prioritize infrastructure management systems [39], to assess last mile delivery services [40], to identify strategic ports [26], and to study factors affecting mode choice [41]. As regards location problems, AHP was recently used as a support framework to select the best site for a distribution center [42] and a micro-consolidation center [43]. In this research work, the AHP was used to prioritize potential sensor locations for a TMS, considering multiple objectives that the system can address. These objectives and criteria were identified by a literature review and proposed by a panel of experts belonging to different agencies and, therefore, expressing different and conflicting needs. From this perspective, the AHP is particularly suitable [44] and it helps the DMs to understand the link between their preferences and the final outcomes [8]. Furthermore, it is very flexible since it allows to evaluate each alternative in agreement with different criteria, thus identifying different sets of locations optimally addressing each objective. The targeted topic allowed to define a clear hierarchical framework, which was built so that selected criteria are independent among each other. Moreover, the developed procedure is intended to be applied to a static decision, since it concerns the location problem of permanent counting stations.

2.3. Fuzzy Delphi

The Delphi method was developed in the 1950s [45] and is a decision-making procedure that aggregates the opinions from a panel of experts to build consensus and a holistic final evaluation [46]. It is a statistical iterative approach based on a series of questionnaires and feedback with anonymous responses of people with different background and expertise [47,48]. Nevertheless, in many cases, judgements cannot be converted into quantitative values without loss of meaning [49]. Therefore, in order to consider the vagueness, imprecision, and subjective nature of human expressions, a combination of Fuzzy set theory with the Delphi approach was proposed [50,51]. The Fuzzy Delphi method allows to reduce the number of iterations needed to reach the consistency of experts' judgements, thus decreasing the time effort to administer and collect questionnaires [52]. In the traditional Delphi, if members of the panel do not change their opinions to meet the average value of all the group, they could be excluded; Fuzzy Delphi allows to prevent this potential loss of information, by assigning a membership function to each response [52]. The method has been widely adopted in many applications and has aften been coupled with the AHP [41,48,51]. In the presented research study, the Fuzzy Delphi was applied to reduce the number of criteria to be considered in the AHP, by collecting judgements from experts belonging to different agencies.)

3. Methodology

3.1. Adopted framework

The steps of the adopted procedure are summarized in the flowchart shown in Fig. 2. First, potential objectives for which data from a TMS can be used and the criteria to evaluate these objectives were collected (block 1). The analysis was carried out considering previous works on the topic and experts' proposals. After that, the identified objectives, criteria and candidate locations were organized into a hierarchical structure (block 2), where the overall goal of the procedure (i.e., the selection of locations for a TMS) occupies the highest level, followed by objectives, criteria and alternatives; each criterion was connected with the specific objective that it can serve. Then, Fuzzy Delphi was applied to select the criteria that the panel considered as appropriate to evaluate each objective (block 3). In this way, the number of criteria was reduced, and the final framework was generated with the selected ones (block 4). The resulting hierarchical structure was the input of the AHP (block 5). The method allows to estimate the weights of both objectives and criteria (block 6). The performance of the alternatives was quantified by designing and applying specific indicators for each criterion (block 7); In this way, an automated procedure could be implemented for their estimation, thus preventing the panel from performing many pairwise comparisons among the 83 alternatives. Lastly, weights of objectives and criteria, and performance of candidate locations were combined to obtain the ranking of the sites (block 8); specifically, the rank was developed in agreement with each objective and the overall goal of the procedure, thus allowing to identify the best set from multiple perspectives, corresponding to the potential objectives of the TMS. The main steps of the Fuzzy Delphi and AHP are described in the following.

3.2. Fuzzy Delphi

The main iterative steps of the Fuzzy Delphi are summarized below [41,49,51,53]:

1 For each criterion connected to an objective in the hierarchical framework, experts were asked to consider the inclusion of that criterion for the evaluation of that objective.

2 Experts' opinions were converted into triangular fuzzy numbers [49, 51]. It is worth noting that, to represent the uncertainty in responses, larger triangular fuzzy number were adopted for judgements near the neutral answer. In this way, a triangular fuzzy number $\widetilde{w}_{kj} = (a_{kj}, b_{kj}, c_{kj})$ was associated to each criterion j and each expert k. After that, a triangular fuzzy number $\widetilde{w}_j = (a_j, b_j, c_j)$, representing the average judgment of all the experts on the criterion j, was generated [49]:

$$a_j = min_k\{a_{kj}\}$$

$$b_j = \frac{1}{n}\sum_{K=1}^{n} b_{kj}$$

$$c_j = max_k\{c_{kj}\}$$

Where n is the number of experts.

1 Each fuzzy number $\widetilde{w}_j$ is defuzzyied by using the centre of gravity technique [49]:

$$w_j = \frac{a_j + b_j + c_j}{3}$$

2 For the iterations after the first one, the consensus on each indicator is checked, by comparing the value of w_j at the current iteration with the corresponding value at the previous iteration. If the difference is less than 1 for all the criteria, the iterative procedure stops and the following step can be performed. If the difference is more than 1, another iteration is to be carried out starting from step 1; in particular, a new questionnaire is administered to the experts, where the crisp number w_j for the previous iteration is shown for each indicator.

3 Criteria are screened and selected based on the following rule [51]:
- If $w_j \geq \overline{w}$, criterion j is selected
- If $w_j < \overline{w}$, criterion j is rejected

Where $\overline{w}$ is the average judgement value among all the criteria.

3.3. Analytic hierarchy process

The following steps of the AHP were applied at each hierarchical level, specifically performing pairwise comparisons among objectives and among criteria connected to each objective:

1 Experts perform paired comparisons between all the items belonging to a group of objectives or criteria whose weights are to be estimated. DMs express the relative importance between two items i and j using the 9-level linguistic scale proposed by Saaty [54]. The same scale is adopted to convert judgements to numeric values that are used to generate the reciprocal matrix A of size n x n (where n is the number of elements to be evaluated), obtained as the aggregation of all experts' judgements:

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{nn} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & \dots & 1 & \dots \\ a_{nn} & a_{1n} & \dots & 1 \end{bmatrix}$$

Where each element a_{ij} represents the relative preference of i to j and is equal to:

$$a_{ij} = \frac{w_i}{w_j}$$

Where w_i and w_j are respectively the weights of i and j to be estimated.

1 The weights of the n elements are calculated by using the eigenvalue approach implemented by Saaty [27]. Following this procedure, the largest eigenvalue of the matrix A (λ_{max}) is used to solve the equation below, to estimate the vector of weights w:

$$Aw = \lambda_{max} w$$

Which is valid if pairwise comparisons are wholly consistent, i.e. if the following relationship holds:

$$a_{ij} = a_{ik}\ x\ a_{kj}\ \forall i, j, k = 1,\ \dots,\ n$$

1 The consistency of judgements is checked by calculating the Consistency Index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

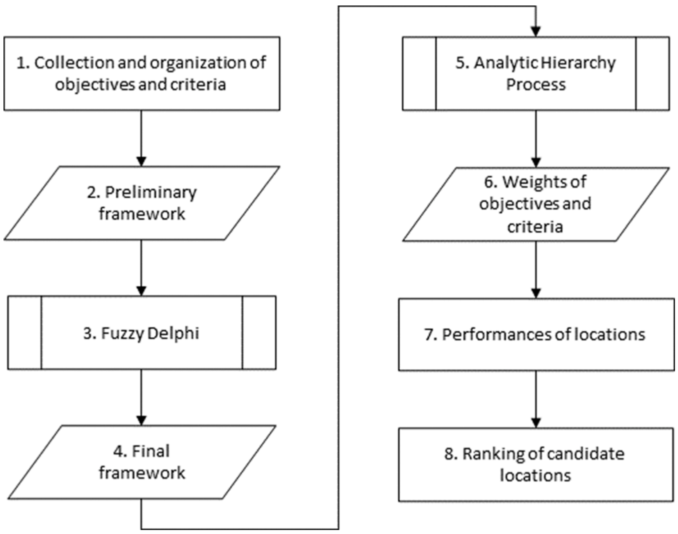

Fig. 1. Flowchart of the adopted procedure.

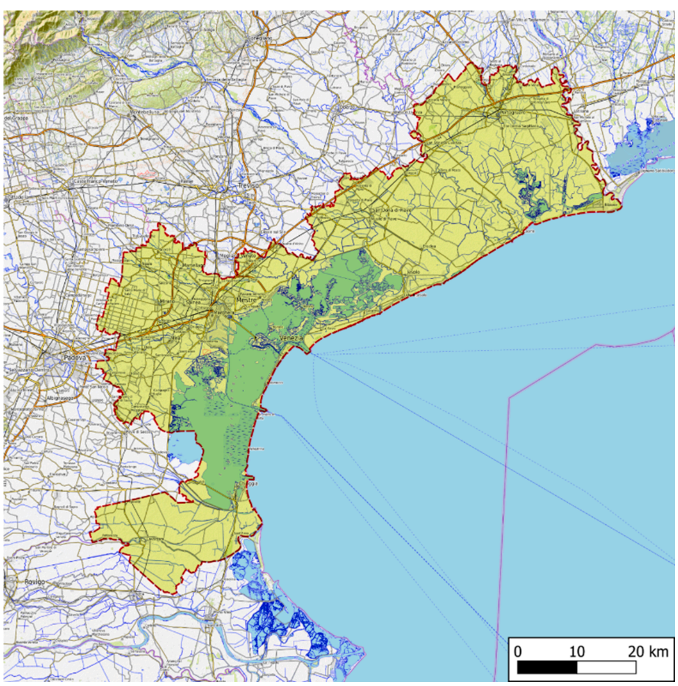

Fig. 2. Study area.

And the Consistency Ratio (CR):

$$CR = \frac{CI}{RI}$$

Where RI is the Random Index, calculated as the average CI of randomly generated reciprocal matrices of size $n \; x \; n$ [55]. A CR lower than 0.1 is considered acceptable, otherwise judgements are considered random and the matrix A should be re-estimated.

Once the relative weights of objectives and criteria, and performance of alternatives are estimated, the final performance of alternatives with respect to each objective is calculated as [27]:

$$p_a^o = \frac{\sum_{j=1}^{J} p_a^j \; x \; w_j^o}{\sum_{j=1}^{J} w_j^o}$$

Where j ($j = 1, \ldots, J$) is an index associated to the criteria linked to objective o, w_j^o is the relative weight of criterion j with respect to objective o, and p_a^j is the performance of alternative a with respect to criterion j. Similarly, the performance of alternatives with respect to the overall goal is estimated as [27]:

$$p_a^g = \frac{\sum_{o=1}^{O} p_a^o \; x \; w_o^g}{\sum_{o=1}^{O} w_o^g}$$

Where O is the total number of objectives and w_o^g is the relative weight of objective o with respect to the overall goal (g).

4. Case study

4.1. Study area

The study area is the Città Metropolitana di Venezia (Italy), and it is highlighted in Fig. 1. The zone is approximately 2500 square kilometres, with about 340 inhabitants per square kilometre. The road network includes many types of roads, ranging from local roads to highways, that are classified in agreement with the administrative unit which is responsible for. The aim of the work was to provide a framework to support the DMs in the selection of sites where sensors of a TMS could be placed. These were continuous count sensors to be installed roadside; therefore, each location corresponds to a road section. Counting instruments can measure the traffic volume, the speed of vehicles and vehicle types. 83 candidate locations were defined by the transportation agency; 12 belonged to National roads, 19 to Regional roads, 50 to Provincial roads, and 2 to Local roads. A panel of experts was selected, with people belonging to different agencies that could benefit from the data collected through the TMS. Specifically, the following agencies were considered: transportation, mobility, urban planning, and environment. The group was composed of 14 members, in line with what was suggested by previous authors [48], who had sufficient knowledge and interest for the topic [47]. To collect responses for Fuzzy Delphi and AHP, specific questionnaires were designed and administered online.

4.2. Application of the Fuzzy Delphi analytic hierarchy process

After a literature review and a discussion with experts, a preliminary list of objectives and criteria was produced. The analysis highlighted that data collected through a TMS can address many different objectives. The first one is the transportation system planning, which includes the evaluation of network performance and the forecasting of projections of future travels [15,56,57]; these activities often need travel demand and traffic simulation models, which can be calibrated and applied using information retrieved from a TMS, such as vehicle volumes, speeds, and travel times. The second identified objective is traffic management and operations; for example, the generation of information for travellers, the management of control junctions and the enforcement of congestion pricing measures and specific access regulations [1,23,58]. Furthermore, data collected through a TMS can be used to evaluate and improve road safety, by applying proposed methods to detect or forecast an accident [59,60]. The third objective is the management of special planned or unplanned events and the analysis of the transportation systems after their occurrence; the first include fairs, sport events, and festivals, while the latter include natural and manmade disasters [61–64]. The last identified objective is related to environmental applications, such as the estimation of vehicle emissions and the evaluation of the relationship between traffic flows and air quality [65].

As regards criteria for evaluating these identified objectives, the first criterion refers to the possibility of using collected data to estimate or update the Origin/Destination matrix, to simulate the traffic flows in the road network. A group of criteria regards the accessibility of specific locations (motorway entrances/exits, train stations, harbours, airports, logistic hub, and intermodal terminals), which are in line with strategic

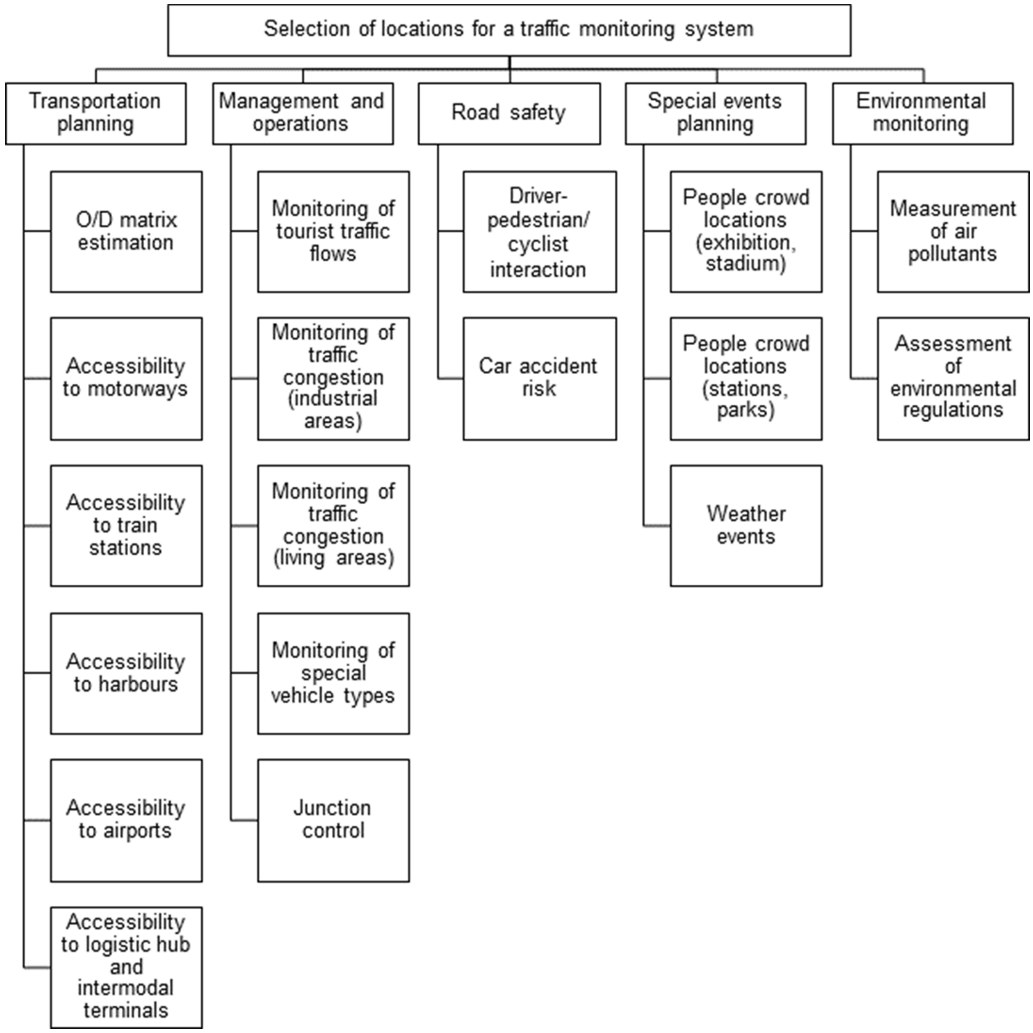

Fig. 3. Hierarchical structure of objectives and criteria.

sites defined by a plan developed by the Veneto Region [66]. "Monitoring of tourist traffic flows" was included since in summer period there is a large number of tourists on the seaside, with high traffic flows. Criteria related to congestion were added to evaluate the periodic increase in vehicle flows near the main attractors and generators (such as industrial and living areas). "Monitoring special vehicle types" refers to the ability of the TMS to provide information for the management of a specific category of vehicles, for example to monitor the enforcement of access restrictions of heavy vehicles. Furthermore, data can be adopted to manage and monitor main junctions in the area ("Junction control"). In the area there are many bicycle/pedestrian paths belonging to local, regional, and national bike networks, therefore, the TMS can also provide useful information to analyse potential traffic conflicts between walkers/cyclists and vehicles ("Driver-pedestrian/cyclist interaction"). In addition, the recorded data can be used to update specific local road safety plans ("Car accident risk"). Specific criteria considering places where people could gather for special events were included (such as exhibitions, stadiums, stations and main parks). TMS was found to be an essential part in the design and management of extraordinary events such as evacuation; since flooding could occur in some zones, the criterion "Weather event" was added to the list. Lastly, "Measurement of air pollutants" allows to consider the importance of the traffic monitoring site in relation to vehicle pollutant emissions; moreover, the TMS can be adopted to analyse the effectiveness of specific regulations to improve air quality ("Assessment of environmental regulations").

The identified objectives and criteria were organized in the

Table 1
Linguistic scale and corresponding crisp and fuzzy number.

Linguistic variable	Crisp number	Triangular fuzzy number
Extremely disagree (ED)	0	(0,0,1)
Disagree (D)	1	(0,1,3)
Moderately disagree (MD)	3	(1,3,5)
Neutral (N)	5	(3,5,7)
Moderately agree (MA)	7	(5,7,9)
Agree (A)	9	(7,9,10)
Extremely agree (EA)	10	(9,10,10)

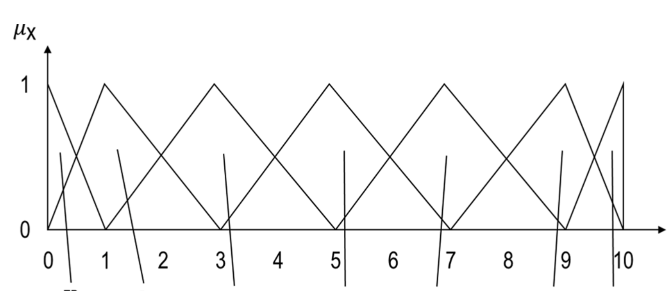

Fig. 4. Graphical representation of considered triangular fuzzy numbers

Table 2
Crisp numbers of average experts' opinion for criteria.

Criterion	w_j^1	w_j^2	$\lvert w_j^1 - w_j^2 \rvert$	Decision
O/D matrix estimation	6.10	5.90	0.20	Selected
Accessibility to motorways	7.21	7.90	0.69	Selected
Accessibility to train stations	7.29	7.90	0.61	Selected
Accessibility to harbours	6.24	6.79	0.55	Rejected
Accessibility to airports	7.12	7.10	0.02	Rejected
Accessibility to logistic hub and intermodal terminals	7.24	7.12	0.12	Rejected
Monitoring of tourist traffic flows	8.83	8.74	0.09	Selected
Monitoring of traffic congestion near industrial areas	7.86	7.81	0.05	Selected
Monitoring of traffic congestion near living areas	7.36	7.21	0.15	Selected
Monitoring of special vehicle types	7.24	7.05	0.19	Rejected
Junction control	7.24	7.86	0.62	Selected
Driver-pedestrian/cyclist interaction	8.05	8.00	0.05	Selected
Car accident risk	8.00	8.07	0.07	Selected
People crowd locations (exhibition, stadium)	5.64	5.29	0.35	Rejected
People crowd locations (stations, park)	6.95	6.86	0.09	Rejected
Weather events	6.98	6.90	0.08	Rejected
Measurement of air pollutants	7.33	7.21	0.12	Selected
Assessment of environmental regulations	7.26	7.21	0.05	Selected

hierarchical structure shown in Fig. 3. As one can note, the overall goal of the procedure is placed on the top; objectives that can be achieved using data collected through a TMS are on the lower level; while criteria to evaluate them are on the third level. The structure can be easily understood by experts, providing them with a clear hierarchy describing the connection among its components and to the overall goal of the procedure.

After that, the Fuzzy Delphi method was applied to identify the criteria to evaluate the objectives. In particular, judgements from the panel of experts were provided through a linguistic scale with 7 levels, ranging from "Extremely disagree" to "Extremely agree", as reported in Table 1. Each linguistic variable was associated to a crisp and a triangular fuzzy number. Fig. 4 shows the adopted triangular fuzzy numbers corresponding to the linguistic variables reported in Table 1.

The results of the Fuzzy Delphi are reported in Table 2, where w_j^k refers to the crisp number of average experts' opinion for criterion j and iteration k of the method. In the second round, the difference in the average judgment between the second and the first iteration ($\lvert w_j^1 - w_j^2 \rvert$) was found to be lower than 1 for all the criteria, therefore the iterative procedure was stopped. The threshold value for criteria selection ($\overline{w}$) was 7.27. Therefore, criteria with a judgement score greater than this value were selected. By observing Table 2 one can note that the final crisp numbers of experts' judgements for criteria "People crowd locations (exhibition, stadium)", "People crowd locations (stations, park)" and "Weather events" (5.29, 6.86 and 6.90, respectively) were lower than the defined threshold; for this reason, they and the related objective "Special events planning" were not included in the following steps of the procedure.

However, other criteria in addition to those retained by the application of the rule described in section 3.2.1 were considered. These include "O/D matrix estimation", "Monitoring of traffic congestion near living areas", "Measurement of air pollutants" and "Assessment of environmental regulations". The first two criteria were selected after a discussion with the agency responsible for the design of TMS, who considered them essential elements. It is worth mentioning that a specific analysis of judgements of experts belonging to this agency was performed; results exhibited an average score of 10 and 8 for these two criteria, respectively, and $\overline{w}$ was equal to 7.73. Furthermore, "Measurement of air pollutants" and "Assessment of environmental regulations" criteria were retained since their scores were very close to the selection threshold and their removal would have implicated the exclusion of "Environmental monitoring" objective from the AHP.

Table 3
Linguistic and cardinal scale for pairwise comparisons.

Linguistic explanation	Intensity of importance
i is equally important to *j*	1
i is slightly more important than *j*	3
i is moderately more important than *j*	5
i is strongly more important than *j*	7
i is extremely more important than *j*	9
Intermediate values of preferences	2,4,6,8

Then, the AHP was applied to the final hierarchical structure of objectives and criteria. Specifically, the 9-level linguistic scale adopted for the pairwise comparisons is reported in Table 3.

The weights of objectives and criteria estimated through the AHP are represented in Fig. 5, Fig. 6 and Fig. 7. In particular, Fig. 5 depicts the relative weights of the objectives with respect to the overall goal of the procedure and highlights that "Road safety" was considered the most important objective to achieve through a TMS. This is a rather expected result, since it is common opinion that safety is a primary aim of many activities, therefore, in pairwise comparisons, this objective often received the highest priority. Otherwise, the weight of "Environmental monitoring" is the lowest one, pointing out that the experts considered that data collected through a TMS cannot be very useful for the analysis related to that topic.

Fig. 6 shows the relative weights of the criteria with respect to the objective they are connected to. For the "Transportation planning" objective, "O/D matrix estimation" criterion received the highest weight, although it was discarded by the criteria selection procedure. This is due to the different approach of the Fuzzy Delphi and AHP to assess the importance of elements. Specifically, in the first method, the assessment of criteria is based on absolute terms, whereas, in the second approach, the evaluation is based on relative terms, by comparing the relative importance of pairs of criteria. For this reason, on the one hand, Fuzzy Delphi suggested that the "O/D matrix estimation" criterion was not indicated as an indicator useful to evaluate the "Transportation planning" objective; on the other hand, the results of the AHP highlighted that the criterion is the most important to evaluate that objective, among the ones proposed for that objective. The same explanation applies to the "Monitoring of traffic congestion near living areas", which exhibited the highest weight among the criteria related to the "Management and operations" objective. A large difference in weight value was observed for the "Monitoring of traffic congestion near industrial area" criterion, if compared to the other three criteria, probably because the topic is not considered a critical issue for the transportation system in the area. As regards "Road safety", the experts attributed slightly more importance to the risk of accidents for cars rather than for pedestrians and cyclists. Lastly, the two criteria associated with "Environmental monitoring" almost shared the same priority level.

Fig. 7 reports the absolute weights of the criteria with respect to the overall goal, corresponding to the importance levels of the criteria in the selection of sensor locations for a TMS. As expected, the two criteria related to the "Road safety" objective showed the highest weights. The criteria "O/D matrix estimation", "Monitoring traffic congestion near living areas", "Measurement of air pollutants" and "Assessment of environmental regulations" had a similar weight. Interestingly, the criteria belonging to this group are related to different objectives. This indicates that the final ranking of sites is affected by all objectives, confirming the choice of considering multiple objectives that a TMS can address.

The weights of the objectives and criteria calculated by the AHP were combined with performance of each alternative site, which were quantified by specific indicators. The adopted methods for their estimation are summarized in Table 4. Input data were obtained from official repositories of Città Metropolitana di Venezia [67,68], Veneto Region

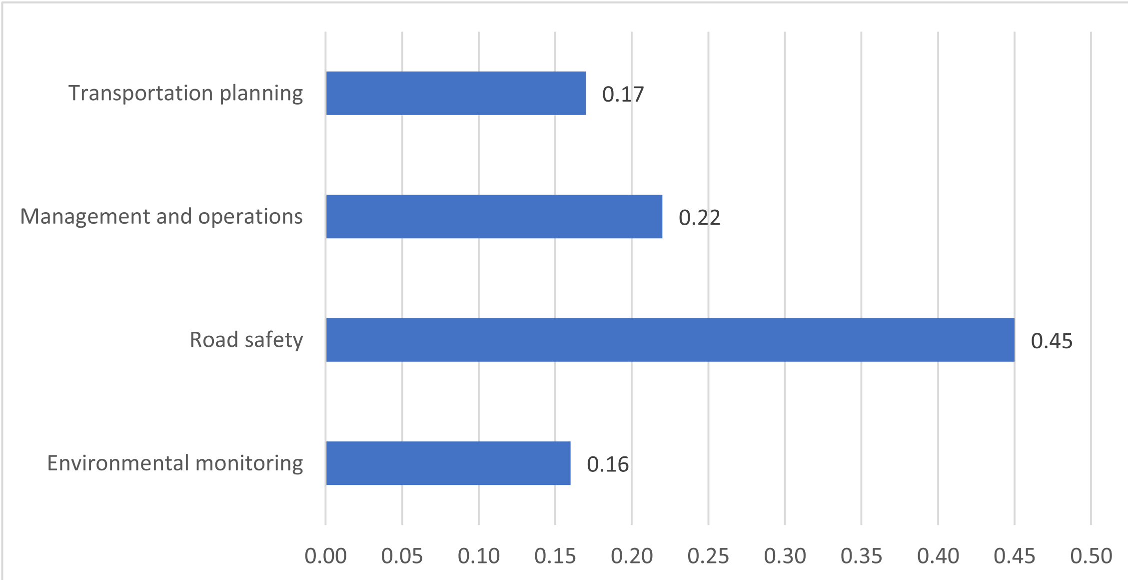

Fig. 5. Relative weights of objectives respect to the overall goal.

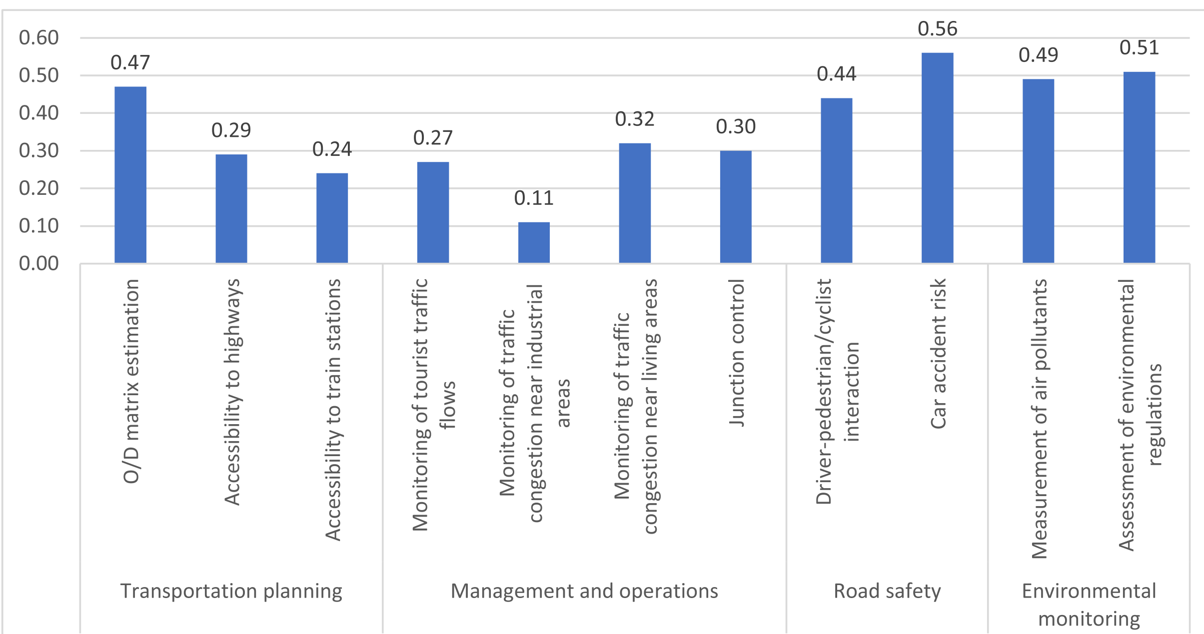

Fig. 6. Relative weights of criteria in regard to objectives.

[69–72], Italian National Institute of Statistics [73] and Automobile Club d'Italia [74]. Further details are reported in the following.

As regards the "O/D matrix estimation" criterion, many approaches have been proposed to identify the best sensor locations in order to estimate the Origin/Destination matrix, such as the O/D covering rule [13,19,75–77], Maximal flow fraction rule [13,75,76], Maximal flow intercepting rule [13,19,75,76], Link independence rule [13,75,76], Route covering rule [13,19,78,79], Maximal O/D demand fraction rule [10,13], Maximal net flow captured rule [13,76] and Maximal net O/D flow captured [13,19,80]. However, many methods require a traffic model of the study area, which was not available during the development of the research, therefore, in this phase, the Maximal flow intercepting rule was adopted. In particular, the value of the Average Daily Traffic obtained from past on-site surveys [68,69,71] was associated with each candidate section.

For the estimation of the next criteria, the OpenStreetMap road network was used in a GIS software. The location of motorway exits and train stations was obtained from the Open Geography Portal of the Veneto Region [72] and verified with GoogleMaps and OpenStreetMaps. To quantify the criterion related to tourist traffic flows, the following value was calculated for each municipality (m) in the area:

$$TR_m = \left(\frac{t_s}{t_w}\right)_m$$

where t_s represents the number of tourists during summer period (from May to August) and t_w the corresponding number during winter period (from September to April) [70]. After that, for each candidate location (l), the criterion was quantified as:

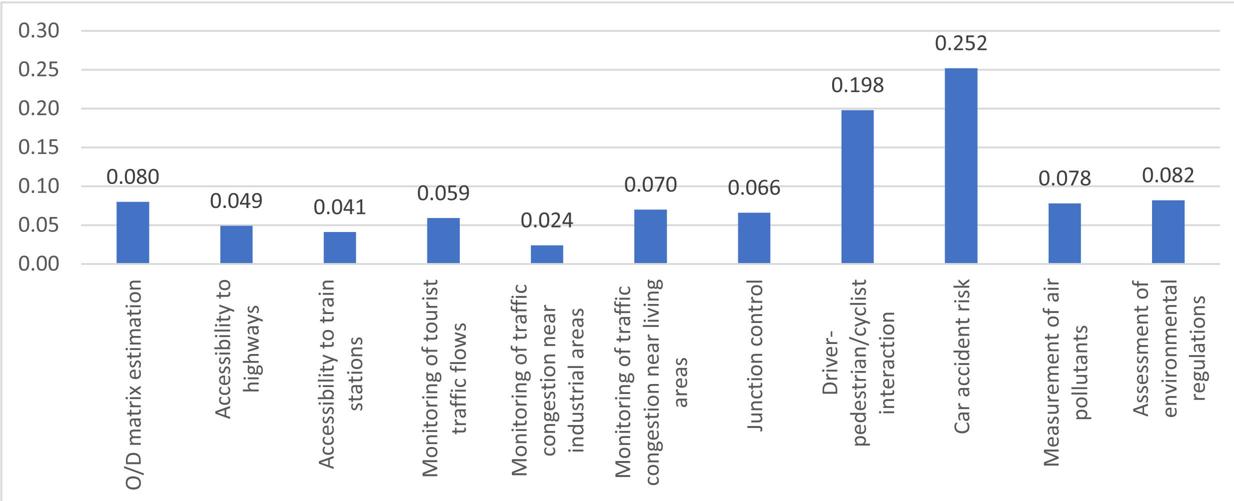

Fig. 7. Absolute weights of criteria in regard to the overall goal.

Table 4
Adopted procedures to estimate the performance values of selected criteria.

Criterion	Method
O/D matrix estimation	Average Daily Traffic from past on-site surveys
Accessibility to motorways	Road distance of the candidate location from the nearest highway exit
Accessibility to train stations	Road distance of the candidate location from the nearest train station
Monitoring of tourist traffic flows	Road distance of the candidate location from all the municipalities weighted by the tourism attractiveness
Monitoring of traffic congestion near industrial areas	Road distance of the candidate location from the nearest major industrial area (at least provincial level)
Monitoring of traffic congestion near living areas	Road distance of the candidate location from the nearest major town (with more than 15.000 inhabitants)
Junction control	Road distance of the candidate location from the nearest junction between provincial/regional/ national road
Driver-pedestrian/cyclist interaction	Road distance of the candidate location from the nearest junction with pedestrian/cyclist path
Car accident risk	Average number of car accidents (2019-2015) per unit length
Measurement of air pollutants	Road distance of the candidate location from the nearest air quality monitoring station
Assessment of environmental regulations	Road distance of the candidate location from the nearest major town (with more than 15.000 inhabitants)

$$C_l = \sum_m \frac{TR_m}{dist\{l,m\}}$$

where $dist\{l,m\}$ is the distance between the candidate location (l) and the administrative center of the municipality (m).

The "Car accident risk" criterion was quantified by using data provided by the Automobile Club d'Italia from 2015 to 2019 [74]; the dataset contains the number of vehicle accidents in each road and municipality. Therefore, the road network was divided into segments following the administrative boundaries of the municipalities and the road name. After that, each candidate section (l) was associated with the segment (s) to which it belongs, and the criterion was estimated as:

$$C_l = \frac{Acc_s}{Len_s}$$

where Acc_s is the number of accidents recorded in segment s during the period 2015-2019 and Len_s is the length of segment s.

Since the criteria were quantified using different scales and units of measurement, values obtained by applying methods reported in Table 4 were normalized. In this way, comparable performance values for all the criteria were estimated. It is worth mentioning that the procedure is extremely flexible, therefore changes in the quantification approaches can be easily implemented.

The final performance values of candidate sensor locations are reported in Fig. 8, in accordance with the considered objectives and the overall goal of the procedure. In addition, the figure shows the obtained level of priority with different colours, where darker colours correspond to higher levels. Since the maximum number of sections to select was 50, the final set is composed by locations with a level of priority greater or equal to that value. As one can note, different ranks were obtained depending on the considered objective, therefore differing final sets of locations can be selected. This confirms the great flexibility of the adopted procedure, which allows to evaluate each candidate site in accordance with a specific objective, as well as the overall goal. Therefore, the final selection of sensor locations can be defined depending on the needs that the TMS has to satisfy. The analysis of results indicates that 84% of the locations belonging to the final set defined following the overall goal were selected even in accordance with the "Road safety" objective, 74% in accordance with the "Management and operations" objective, 70% in accordance with the "Environmental monitoring" objective and 68% in accordance with the "Transportation planning" objective. This highlights that the final set is quite stable, since more than half of the final locations for the overall goal is shared with all the objectives. Furthermore, the sites that could be selected independently on the objective for which they are evaluated represent an ideal solution for the decision maker, because, in this way, these sensors can be used for all the considered objectives, thus maximizing the retrieved information. The number of these sites is 18, corresponding to the 36% of the final set, suggesting a relatively high robustness of the final selection.

5. Conclusions

This paper presented the development and application of a procedure to select the best locations of a fixed number of permanent count sensors for a road Traffic Monitoring System (TMS). The approach explicitly considers that the TMS can serve multiple objectives through collected data and provides decision makers with a transparent and flexible method to rank potential sites where instruments can be installed. The adopted procedure is based on the Fuzzy Delphi Analytic Hierarchy Process and was applied to the case study of the Città

Fig. 8. Ranking of the candidate locations in regard to the considered objective and the overall goal.

Table A.1
List of identified objectives of a TMS and corresponding sources.

Objective of TMS	Sources
Transportation planning	[1,81–86]
Management and operations	[1,87–89]
Road safety	[1,59,60,81,90]
Special events planning	[1,61–64,81,91–93]
Environmental monitoring	[65,82]

Table A.2
List of identified criteria and corresponding sources.

Criterion	Sources
O/D matrix estimation	[10,13,19,75–79]
Accessibility to motorways	[66,94]
Accessibility to train stations	[66,94]
Accessibility to harbours	[66,94]
Accessibility to airports	[66,94]
Accessibility to logistic hub and intermodal terminals	[66,94]
Monitoring of tourists traffic flows	[81]
Monitoring of traffic congestion near industrial areas	Experts' proposal
Monitoring of traffic congestion near living areas	Experts' proposal
Monitoring of special vehicle types	[1]
Junction control	[87,88]
Driver-pedestrian/cyclist interaction	[81]
Car accident risk	[81]
People crowd locations (exhibition, stadium)	[81]
People crowd locations (stations, parks)	[95]
Weather events	[94,96]
Measurement of air pollutants	[65]
Assessment of environmental regulations	[97]

Metropolitana di Venezia (Italy). The input data were provided by a panel of experts belonging to different agencies, expressing different and conflicting needs that could be addressed through a TMS. Specifically, potential objectives of the TMS and criteria to evaluate them were identified through a literature review and discussion with experts, and then screened by applying the Fuzzy Delphi. Results were used to generate a structure where objectives, criteria and potential sites were hierarchically connected. Then, the Analytic Hierarchy Process was used to estimate the importance of items in the structure and prioritize the potential sensor locations. The results showed that "Road safety" was considered the most important objective to achieve through a TMS; respondents reported low relevance for the "Environmental monitoring" objective. Furthermore, the analysis of the weights of criteria indicated that the final ranking of the sites is affected by all objectives, supporting the decision to evaluate multiple objectives that the TMS can address. In addition, differing final ranks were obtained according with the considered objectives, however 36% of locations could be selected independently on the perspective for which they are evaluated. The proposed procedure was easily understood by experts, since it provided them with a clear hierarchy describing the connection among its components and the overall goal of the procedure. This is an important goal since it prevents decision makers from losing the link between their preferences and outcomes, thus increasing their confidence in the final choices. In addition, the method was very flexible, since it allowed to evaluate each candidate location according with specific criteria, objectives, and the overall goal. Therefore, different final sets could be optimally selected to address needs that the TMS can satisfy. Future research steps include a sensitivity analysis to evaluate the robustness of the obtained final ranks of locations and the investigation of the potential impacts of the membership of experts to a particular agency.

Appendix A

Table A.1 reports the set of identified objectives that can be reached with a TMS and the previous works where they have been considered.

Table A.2 summarizes the identified criteria for evaluating the objectives reported in Table A.1.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

The authors do not have permission to share data.

Acknowledgements

The authors thank the head of the transportation agency of the Città Metropolitana di Venezia for his support in building the panel of experts.

References

[1] Federal Highway Administration U.S. Department of Transportation, Traffic Monitoring Guide, 2016. http://www.fhwa.dot.gov/policyinformation/tmguide/.
[2] W. Sun, H. Shao, L. Shen, T. Wu, W.H.K. Lam, B. Yao, B. Yu, Bi-objective traffic count location model for mean and covariance of origin–destination estimation, Expert Syst. Appl. 170 (2021), 114554, https://doi.org/10.1016/j.eswa.2020.114554.
[3] R. Ceccato, G. Gecchele, R. Rossi, M. Gastaldi, Cost-effectiveness analysis of origin-destination matrices estimation using floating car data. Experimental results from two real cases, Transp. Res. Procedia. 62 (2022) 541–548, https://doi.org/10.1016/j.trpro.2022.02.067.
[4] M.S. Iqbal, C.F. Choudhury, P. Wang, M.C. González, Development of origin-destination matrices using mobile phone call data, Transp. Res. Part C Emerg. Technol. 40 (2014) 63–74, https://doi.org/10.1016/j.trc.2014.01.002.
[5] F. Yang, P.J. Jin, Y. Cheng, J. Zhang, B. Ran, Origin-destination estimation for non-commuting trips using location-based social networking data, Int. J. Sustain. Transp. 9 (2015) 551–564, https://doi.org/10.1080/15568318.2013.826312.
[6] X. Chen, Z. Li, Y. Yang, L. Qi, R. Ke, High-resolution vehicle trajectory extraction and denoising from aerial videos, IEEE Trans. Intell. Transp. Syst. 22 (2021) 3190–3202, https://doi.org/10.1109/TITS.2020.3003782.
[7] J. Guo, B.L. Smith, G. Zhang, Information technology used to evaluate imontraditional traffic monitoring systems, Transp. Res. Rec. (2007) 1–7, https://doi.org/10.3141/2024-01.
[8] C. Macharis, A. Bernardini, Reviewing the use of multi-criteria decision analysis for the evaluation of transport projects: Time for a multi-actor approach, Transp. Policy. 37 (2015) 177–186, https://doi.org/10.1016/j.tranpol.2014.11.002.
[9] L. Bianco, G. Confessore, P. Reverberi, A network based model for traffic sensor location with implications on O/D matrix estimates, Transp. Sci. 35 (2001) 50–60, https://doi.org/10.1287/trsc.35.1.50.10140.
[10] E. Cipriani, G. Fusco, S. Gori, M. Petrelli, Heuristic methods for the optimal location of road traffic monitoring stations, IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC. (2006) 1072–1077.
[11] E. Castillo, M. Nogal, A. Rivas, S. Sánchez-Cambronero, Observability of traffic networks. optimal location of counting and scanning devices, Transp. B. 1 (2013) 68–102, https://doi.org/10.1080/21680566.2013.780987.
[12] H. Fu, W.H.K. Lam, H. Shao, X.P. Xu, H.P. Lo, B.Y. Chen, N.N. Sze, A. Sumalee, Optimization of traffic count locations for estimation of travel demands with covariance between origin-destination flows, Transp. Res. Part C Emerg. Technol. 108 (2019) 49–73, https://doi.org/10.1016/j.trc.2019.09.004.
[13] M. Gentili, P.B. Mirchandani, Locating sensors on traffic networks: Models, challenges and research opportunities, Transp. Res. Part C Emerg. Technol. 24 (2012) 227–255, https://doi.org/10.1016/j.trc.2012.01.004.
[14] S.X. He, A graphical approach to identify sensor locations for link flow inference, Transp. Res. Part B Methodol. 51 (2013) 65–76, https://doi.org/10.1016/j.trb.2013.02.006.
[15] W.E. Frawley, Random count site selection process for statistically valid estimations of local street vehicle miles traveled, Transp. Res. Rec. (2007) 43–50, https://doi.org/10.3141/1993-07.
[16] R. Mínguez, S. Sánchez-Cambronero, E. Castillo, P. Jiménez, Optimal traffic plate scanning location for OD trip matrix and route estimation in road networks, Transp. Res. Part B Methodol. 44 (2010) 282–298, https://doi.org/10.1016/j.trb.2009.07.008.
[17] X. Fei, H.S. Mahmassani, Structural analysis of near-optimal sensor locations for a stochastic large-scale network, Transp. Res. Part C Emerg. Technol. 19 (2011) 440–453, https://doi.org/10.1016/j.trc.2010.07.001.

[18] N. Wang, M. Gentili, P. Mirchandani, Model to locate sensors for estimation of static origin-destination volumes given prior flow information, Transp. Res. Rec. (2012) 67–73, https://doi.org/10.3141/2283-07.
[19] T. Larsson, J.T. Lundgren, A. Peterson, Allocation of link flow detectors for origin-destination matrix estimation - A Comparative Study, Comput. Civ. Infrastruct. Eng. 25 (2010) 116–131, https://doi.org/10.1111/j.1467-8667.2009.00625.x.
[20] F. Simonelli, A. Papola, V. Marzano, I. Vitiello, Methodology for locating link count sensors that accounts for reliability of prior estimates from origin-destination matrices, Transp. Res. Rec. (2011) 182–190, https://doi.org/10.3141/2263-20.
[21] E. Castillo, P. Jiménez, J.M. Menéndez, A.J. Conejo, The observability problem in traffic models: Algebraic and topological methods, IEEE Trans. Intell. Transp. Syst. 9 (2008) 275–287, https://doi.org/10.1109/TITS.2008.922929.
[22] Y. Liu, N. Zhu, S. Ma, N. Jia, Traffic sensor location approach for flow inference, IET Intell. Transp. Syst. 9 (2015) 184–192, https://doi.org/10.1049/iet-its.2014.0023.
[23] F. Viti, W. Verbeke, C.M.J. Tampère, Sensor locations for reliable travel time prediction and dynamic management of traffic networks, Transp. Res. Rec. (2008) 103–110, https://doi.org/10.3141/2049-12.
[24] M.R.R. Shaon, X. Li, Y.-J. Wu, S. Ramos, Quantitative evaluation of advanced traffic management systems using analytic hierarchy process, Transp. Res. Rec. J. Transp. Res. Board. (2021), 036119812110302, https://doi.org/10.1177/03611981211030256.
[25] A. Sinha, K.C. Strong, M.E. Ozbek, J. Shane, A decision support framework for assessing the contextual factors for complex highway projects, Transp. Res. Rec. 2672 (2018) 77–87, https://doi.org/10.1177/0361198118774162.
[26] S. Carrese, M. Petrelli, A. Renna, A new approach for the identification of strategic Italian ports for container traffic, Transp. Policy. 120 (2022) 47–55, https://doi.org/10.1016/j.tranpol.2022.03.005.
[27] T.L. Saaty, How to make a decision: the analytic hierarchy process, Eur. J. Oper. Res. 48 (1990) 9–26, https://doi.org/10.1016/0377-2217(90)90057-I.
[28] M. Şahin, A comprehensive analysis of weighting and multicriteria methods in the context of sustainable energy, Int. J. Environ. Sci. Technol. 18 (2021) 1591–1616, https://doi.org/10.1007/s13762-020-02922-7.
[29] J.D. Porras-Alvarado, M.R. Murphy, H. Wu, Z. Han, Z. Zhang, M. Arellano, Analytical hierarchy process to improve project prioritization in the Austin District, Texas, Transp. Res. Rec. 2613 (2017) 29–36, https://doi.org/10.3141/2613-04.
[30] H.H. Liu, Y.Y. Yeh, J.J. Huang, Correlated analytic hierarchy process, Math. Probl. Eng. 2014 (2014), https://doi.org/10.1155/2014/961714.
[31] S.I. Ohnishi, T. Yamanoi, H. Imai, On a weight representation for inner dependence method AHP, Isc. '09 - 4th Int. Symp. Comput. Intell. Intell. Informatics, Proc. (2009) 113–117, https://doi.org/10.1109/ISCIII.2009.5342272.
[32] Y.N. Liu, H.H. Wu, An inner dependence analysis dynamic decision-making framework, Sustain 14 (2022), https://doi.org/10.3390/su14105968.
[33] T.L. Saaty, The analytic hierarchy and analytic network measurement processes: Applications to decisions under Risk, Eur. J. Pure Appl. Math. 1 (2007) 122–196, https://doi.org/10.29020/nybg.ejpam.v1i1.6.
[34] R. Ramanathan, Data envelopment analysis for weight derivation and aggregation in the analytic hierarchy process, Comput. Oper. Res. 33 (2006) 1289–1307, https://doi.org/10.1016/j.cor.2004.09.020.
[35] L.C. Leung, D. Cao, On the efficacy of modeling multi-attribute decision problems using AHP and Sinarchy, Eur. J. Oper. Res. 132 (2001) 39–49, https://doi.org/10.1016/S0377-2217(00)00111-9.
[36] M. Ivanco, G. Hou, J. Michaeli, Sensitivity analysis method to address user disparities in the analytic hierarchy process, Expert Syst. Appl. 90 (2017) 111–126, https://doi.org/10.1016/j.eswa.2017.08.003.
[37] G. Improta, M.A. Russo, M. Triassi, G. Converso, T. Murino, L.C. Santillo, Use of the AHP methodology in system dynamics: Modelling and simulation for health technology assessments to determine the correct prosthesis choice for hernia diseases, Math. Biosci. 299 (2018) 19–27, https://doi.org/10.1016/j.mbs.2018.03.004.
[38] D.P. Guegan, P.T. Martin, W.D. Cottrell, Prioritizing traffic-calming projects using the analytic hierarchy process, Transp. Res. Rec. (2000) 61–67, https://doi.org/10.3141/1708-07.
[39] J.T. Smith, S.L. Tighe, Analytic hierarchy process as a tool for infrastructure management, Transp. Res. Rec. (2006) 3–9, https://doi.org/10.3141/1974-03.
[40] J. Du, X. Wang, Matching model for multiple delivery methods in last-mile delivery for online shopping, Transp. Res. Rec. 2676 (2022) 556–572, https://doi.org/10.1177/03611981211036361.
[41] S. Ebrahimi, R. Bridgelall, A fuzzy Delphi analytic hierarchy model to rank factors influencing public transit mode choice: A case study, Res. Transp. Bus. Manag. 39 (2021), 100496, https://doi.org/10.1016/j.rtbm.2020.100496.
[42] Y. He, X. Wang, Y. Lin, F. Zhou, L. Zhou, Sustainable decision making for joint distribution center location choice, Transp. Res. Part D Transp. Environ. 55 (2017) 202–216, https://doi.org/10.1016/j.trd.2017.07.001.
[43] C. Rudolph, A. Nsamzinshuti, S. Bonsu, A.B. Ndiaye, N. Rigo, Localization of relevant urban micro-consolidation centers for last-mile cargo bike delivery based on real demand data and city characteristics, Transp. Res. Rec. 2676 (2022) 365–375, https://doi.org/10.1177/03611981211036351.
[44] D. Manca, S. Brambilla, A methodology based on the analytic hierarchy process for the quantitative assessment of emergency preparedness and response in road tunnels, Transp. Policy. 18 (2011) 657–664, https://doi.org/10.1016/j.tranpol.2010.12.003.
[45] N. Dalkey, O. Helmer, An experimental apllication of Delphi method to use of experts, Manage. Sci. (1963) 458–467. https://www.rand.org/content/dam/rand/pubs/research_memoranda/2009/RM727.1.pdf.
[46] K.C. Sinha, S. Labi, Transportation Decision Making, 2007. https://doi.org/10.1002/9780470168073.
[47] T. Grisham, The Delphi technique: a method for testing complex and multifaceted topics, Int. J. Manag. Proj. Bus. 2 (2009) 112–130, https://doi.org/10.1108/17538370910930545.
[48] L.A. Vidal, F. Marle, J.C. Bocquet, Using a Delphi process and the analytic hierarchy process (AHP) to evaluate the complexity of projects, Expert Syst. Appl. 38 (2011) 5388–5405, https://doi.org/10.1016/j.eswa.2010.10.016.
[49] Y.L. Hsu, C.H. Lee, V.B. Kreng, The application of Fuzzy Delphi Method and Fuzzy AHP in lubricant regenerative technology selection, Expert Syst. Appl. 37 (2010) 419–425, https://doi.org/10.1016/j.eswa.2009.05.068.
[50] A. Ishikawa, M. Amagasa, T. Shiga, G. Tomizawa, R. Tatsuta, H. Mieno, The max-min Delphi method and fuzzy Delphi method via fuzzy integration, Fuzzy Sets Syst 55 (1993) 241–253, https://doi.org/10.1016/0165-0114(93)90251-C.
[51] M. Bouzon, K. Govindan, C.M.T. Rodriguez, L.M.S. Campos, Identification and analysis of reverse logistics barriers using fuzzy Delphi method and AHP, Resour. Conserv. Recycl. 108 (2016) 182–197, https://doi.org/10.1016/j.resconrec.2015.05.021.
[52] Y.F. Kuo, P.C. Chen, Constructing performance appraisal indicators for mobility of the service industries using Fuzzy Delphi Method, Expert Syst. Appl. 35 (2008) 1930–1939, https://doi.org/10.1016/j.eswa.2007.08.068.
[53] Z. Ma, C. Shao, S. Ma, Z. Ye, Constructing road safety performance indicators using fuzzy delphi method and grey delphi method, Expert Syst. Appl. 38 (2011) 1509–1514, https://doi.org/10.1016/j.eswa.2010.07.062.
[54] R.W. Saaty, The analytic hierarchy process-what it is and how it is used, Math. Model. 9 (1987) 161–176, https://doi.org/10.1016/0270-0255(87)90473-8.
[55] T.L. Saaty, Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process, RWS publications, Pittsburgh, PA, 1994.
[56] M. Gastaldi, G. Gecchele, R. Rossi, Estimation of Annual Average Daily Traffic from one-week traffic counts. A combined ANN-Fuzzy approach, Transp. Res. Part C Emerg. Technol. 47 (2014) 86–99, https://doi.org/10.1016/j.trc.2014.06.002.
[57] M. Gentili, P.B. Mirchandani, Survey of models to locate sensors to estimate traffic flows, Transp. Res. Rec. (2011) 108–116, https://doi.org/10.3141/2243-13.
[58] X. Li, Y. Ouyang, Reliable sensor deployment for network traffic surveillance, Transp. Res. Part B Methodol. 45 (2011) 218–231, https://doi.org/10.1016/j.trb.2010.04.005.
[59] T. Geetla, R. Batta, A. Blatt, M. Flanigan, K. Majka, Optimal placement of omnidirectional sensors in a transportation network for effective emergency response and crash characterization, Transp. Res. Part C Emerg. Technol. 45 (2014) 64–82, https://doi.org/10.1016/j.trc.2014.02.024.
[60] G. Gecchele, F. Orsini, M. Gastaldi, R. Rossi, Freeway rear-end collision risk estimation with extreme value theory approach. A case study, Transp. Res. Procedia. 37 (2019) 195–202, https://doi.org/10.1016/j.trpro.2018.12.183.
[61] N. Zou, S.T. Yen, G.L. Chang, A. Marquess, M. Zezeski, Simulation-based emergency evacuation system for Ocean City, Maryland, during hurricanes, Transp. Res. Rec. (2005) 138–148, https://doi.org/10.3141/1922-18.
[62] J. Li, K. Ozbay, B. Bartin, S. Iyer, J. Carnegie, Empirical evacuation response curve during hurricane Irene in Cape May County, New Jersey, Transp. Res. Rec. (2013) 1–10, https://doi.org/10.3141/2376-01.
[63] B. Wolshon, B. McArdle, Temporospatial Analysis of Hurricane Katrina Regional Evacuation Traffic Patterns, J. Infrastruct. Syst. 15 (2009) 12–20, https://doi.org/10.1061/(asce)1076-0342(2009)15:1(12).
[64] R.W. Eck, D.A. Montag, Traffic Effects of Fairs and Festivals on Low-Volume Roads, Transp. Res. Rec. I (2003) 260–264, https://doi.org/10.3141/1819a-38.
[65] R. Rossi, R. Ceccato, M. Gastaldi, Effect of road traffic on air pollution. Experimental evidence from covid-19 lockdown, Sustain 12 (2020) 1–17, https://doi.org/10.3390/su12218984.
[66] Regione Veneto, Piano Territoriale Regionale di Coordinamento - Norme tecniche, 2020. https://www.regione.veneto.it/web/ptrc/ptrc-2020.
[67] Città Metropolitana di Venezia, Piano Territoriale Generale Metropolitano, 2018. https://pianificazione.cittametropolitana.ve.it/ptgm-piano-territoriale-generale-metropolitano.html.
[68] Città Metropolitana di Venezia, Sustainable Urban Mobility Plan, (2022). https://pums.cittametropolitana.ve.it/.
[69] Regione Veneto, PROGETTO SIRSE 2006-2007, 2007. https://trasporti.cittametropolitana.ve.it/pianif_trasp/zip/Pubbl_agg_2006-2007.pdf.
[70] Regione Veneto, Sistema statistico regionale, (2021). https://statistica.regione.veneto.it/index.jsp.
[71] Regione Veneto, PROGETTO SIRSE 2008-2009, 2009. https://trasporti.cittametropolitana.ve.it/pianif_trasp/zip/Pubbl_agg_2008-2009.pdf.
[72] Regione Veneto, Geoportale della Regione Veneto, (2021). https://idt2.regione.veneto.it/.
[73] ISTAT, Censimenti permanenti - Data warehouse, (2021). http://dati-censimentipermanenti.istat.it/#.
[74] ACI, ACI - Incidentalità, (2021). https://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/incidentalita.html.
[75] E. Castillo, J.M. Menéndez, S. Sánchez-Cambronero, Traffic estimation and optimal counting location without path enumeration using bayesian networks, Comput. Civ. Infrastruct. Eng. 23 (2008) 189–207, https://doi.org/10.1111/j.1467-8667.2008.00526.x.
[76] H. Yang, J. Zhou, Optimal traffic counting locations for origin-destination matrix estimation, Transp. Res. Part B Methodol. 32 (1998) 109–126, https://doi.org/10.1016/s0191-2615(97)00016-7.
[77] M.V. Saraswathy, K.P. Isaac, Prioritisation of Traffic Count Locations for Trip Matrix Estimation Using Information Theory, Int. J. Traffic Transp. Eng. 3 (2013) 112–126, https://doi.org/10.7708/ijtte.2013.3(2).02.

[78] H. Yang, C. Yang, L. Gan, Models and algorithms for the screen line-based traffic-counting location problems, Comput. Oper. Res. 33 (2006) 836–858, https://doi.org/10.1016/j.cor.2004.08.011.

[79] T. Koch, R. Van Der Mei, E. Dugundji, The optimization of traffic count locations in multi-modal networks, Procedia Comput. Sci. 130 (2018) 287–293, https://doi.org/10.1016/j.procs.2018.04.041.

[80] P.K.N. Yim, W.H.K. Lam, Evaluation of Count Location Selection Methods for Estimation of O-D Matrices, J. Transp. Eng. Part A Syst. (1998) 376–383.

[81] M. Chowdhury, N. Huynh, S.M. Khan, M.Z. Khan, K. Brunk, M. Torkjazi, S. Islam, M. Keehan, S. Shiri, Cost Effective Strategies for Estimating Statewide AADT, 2019.

[82] WSDOT, Short Count Factoring Guide, Washington DC, United States, 2020.

[83] L. Caggiani, M. Dell'Orco, M. Marinelli, M. Ottomanelli, A Metaheuristic Dynamic Traffic Assignment Model for O-D Matrix Estimation using Aggregate Data, Procedia - Soc. Behav. Sci. 54 (2012) 685–695, https://doi.org/10.1016/j.sbspro.2012.09.786.

[84] L. Caggiani, M. Ottomanelli, D. Sassanelli, A fixed point approach to origin-destination matrices estimation using uncertain data and fuzzy programming on congested networks, Transp. Res. Part C Emerg. Technol. 28 (2013) 130–141, https://doi.org/10.1016/j.trc.2010.12.005.

[85] V. Marzano, A. Papola, F. Simonelli, Limits and perspectives of effective O-D matrix correction using traffic counts, Transp. Res. Part C Emerg. Technol. 17 (2009) 120–132, https://doi.org/10.1016/j.trc.2008.09.001.

[86] K. Ashok, M.E. Ben-Akiva, Estimation and prediction of time-dependent origin-destination flows with a stochastic mapping to path flows and link flows, Transp. Sci. 36 (2002) 184–198, https://doi.org/10.1287/trsc.36.2.184.563.

[87] L. Cruz-Piris, D. Rivera, S. Fernandez, I. Marsa-Maestre, Optimized sensor network and multi-agent decision support for smart traffic light management, Sensors (Switzerland) 18 (2018), https://doi.org/10.3390/s18020435.

[88] M. Tubaishat, Q. Qi, Y. Shang, H. Shi, Wireless sensor-based traffic light control, 2008 5th IEEE Consum. Commun. Netw. Conf. CCNC 2008 (2008) 702–706, https://doi.org/10.1109/ccnc08.2007.161.

[89] X. Li, Y. Ouyang, Reliable traffic sensor deployment under probabilistic disruptions and generalized surveillance effectiveness measures, Oper. Res. 60 (2012) 1183–1198, https://doi.org/10.1287/opre.1120.1082.

[90] G.P. Moynihan, D.J. Fonseca, T. Brumback, H. Fernandes, Evacuation decision support system for road incident detection and characterization, J. Homel. Secur. Emerg. Manag. 6 (2009), https://doi.org/10.2202/1547-7355.1527.

[91] E. Boyd, B. Wolshon, I. Van Heerden, Risk comunication and public response during evacuations: the new orleans experience of hurricane katrina, Public Perform. Manag. Rev. 32 (2009) 437–462.

[92] R.H. Henk, P. Songchitruksa, S. Venglar, G. Lim, others, Prototype design for a predictive model to improve evacuation operations: technical report., 2011.

[93] G. Tan, Z. Liu, Y. Wang, The determination and analysis of traffic congestion evacuation priority, 2010 2nd IITA Int. Conf. Geosci. Remote Sensing, IITA-GRS 2010 2 (2010) 484–487, https://doi.org/10.1109/IITA-GRS.2010.5603003.

[94] K. Wiegand, Challenges of the Day-to-Day Operation of a Traffic Monitoring Program, Atlanta, Georgia, USA, 2016.

[95] S.P. Latoski, W.M. Dunn, B. Wagenblast, J. Randall, M.D. Walker, others, Managing travel for planned special events, 2003.

[96] D.W. Borchardt, D.D. Puckett, others, Real-time data for hurricane evacuation in Texas, 2008.

[97] A. Font, G.W. Fuller, Did policies to abate atmospheric emissions from traffic have a positive effect in London? Environ. Pollut. 218 (2016) 463–474, https://doi.org/10.1016/j.envpol.2016.07.026.